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CANADIAN ELECTRICAL ASSOCIATION
and
CANMET, ENERGY, MINES AND RESOURCES, CANADA

SILICON METAL PRODUCTION IN BRITISH COLUMBIA USING PLASMA TECHNOLOGY A CONCEPTUAL STUDY

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ABSTRACT

This technico-economic study has assessed the potential for the production of chemical grade silicon metal in British Columbia. Thermodynamic and process kinetic considerations have lead to the conceptual design of a transferred arc plasma furnace configuration and associated materials handling system. Cost estimates have been made for a site specific IMW pilot plant facility and its operation aimed at obtaining data on the economics of commercial production. A preliminary analysis is presented which suggests that the availability of high grade quartzite and competitively priced hydro-electric power in the province, combined with a multifaceted and growing international market for chemical grade silicon make it economically attractive to carry out this highly energy intensive smelting process in British Columbia on a commercial scale.

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SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

1. There exists a market for the projected production of 10,000 - 20,000 tonnes/yr of silicon in Western Canada.

2. British Columbia has large deposits of suitable grade quartzite, wood chips, natural gas and competitively priced electric power needed for silicon production using plasma technology.

3. A conceptual design is presented for producing 80 kg/hr of 99+% Siilion metal using a 1 MW pilot plant involving a d-c transferred arc column and a shaft furnace configuration. It is estimated that the pilot plant can be constructed, commissioned and operated over a two year period at a total cost of $2.95 M.

4. Early indications are that plasma technology may offer distinct processing as well as economic advantages over the conventional a-c submerged arc technology for silicon production.

5. It is recommended that the pilot plant study be undertaken to test the technical and economic viability of the plasma process for commercial production.

1.0 INTRODUCTION

Potential for the application of plasma technology in Canada was examined in a report[1] prepared in 1985. In 1986 another study was undertaken to examine opportunities for plasma technology in Western Canada[2]. A short list of promising commodities was identified in that latter study based on the marketing survey. Market potential for silicon metal production was also identified in an independent in-house study carried out by the Ministry of Economic Development in British Columbia[3].

The highly energy intensive carbon reduction of SiO_2 (12,500 - 14,600 kWh/tonne of Si) has been traditionally carried out in ac submerged arc furnaces. A higher power density associated with the transferred arc plasma offers the attractive possibility of silicon smelting in compact plasma transferred arc furnaces (Figure 1). It is noteworthy that silicon smelting has been attempted with non-transferred arc plasma torches in the laboratory using carbon as a reductant[5] and in a 1.5 MW pilot plant using metallic sodium as the reducing agent[6]. Photovoltaic grade silicon was produced successfully in that pilot plant study. However, the cost of silicon so produced, was found economically unattractive. Limited success was achieved in the carbon reduction of silica possibly due to the low thermal efficiency (70-85%) of the non transferred arc plasma. By contrast transferred arcs have efficiencies of the order of 96 percent.

An inductive plasma (rf plasma) reactor has also been used in the laboratory for producing solar grade silicon[7]. Fine silica flour and carbon black were mixed and formed into a 6 mm diameter rod which in turn was subjected to the rf plasma. Maximum silicon content of the product was found to be 33 percent. That process was considered technically feasible. However, the poor heat transfer from the plasma to the reactant and the low yield made the process economically unattractive for large scale use.

The availability of high grade quartzite in the Golden region of British Columbia[8] combined with an abundance of competitively priced hydro-electric power make it an attractive proposition to examine the viability of silicon production in a transferred arc plasma reactor. To illustrate the quality of quartzite, the following is a typical specification in weight % of a sample from the Golden region[8]:

SiO_2	-	99.67
Fe_2O_3	-	0.02
Al_2O_3	-	0.06
CaO	-	0.06
K_2O	-	0.02
MgO	-	0.02
MnO	-	-
Na_2O	-	0.01
TiO_2	-	0.01
Loss on ignition	-	0.12

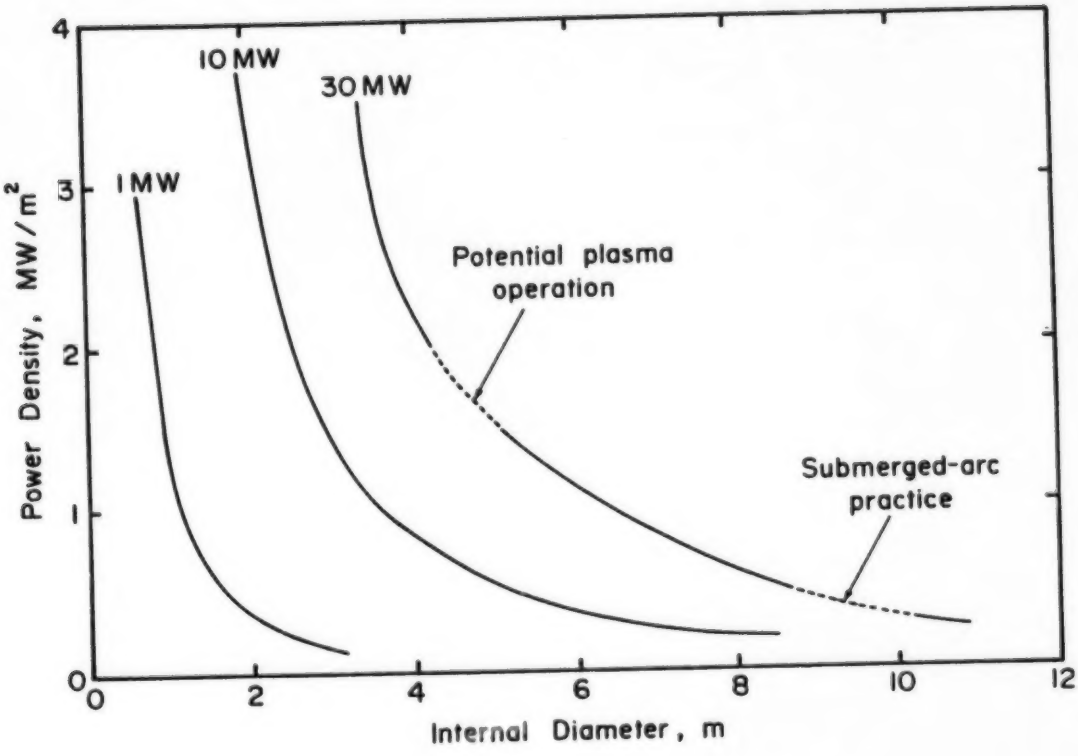

Figure 1: Internal diameter vs power density for transferred arc plasma furnaces (after Curr et.al. - Reference 4)

2.0 MARKETING CONSIDERATIONS

2.1 Product Definition and End Use

According to the U.S. Bureau of Mines (USBM) there are three sub-grades of silicon metal:

- 96% to 99%
- 99% to 99.7%
- Over 99.7% silicon content

The end use of the product in 1986 according to the USBM is as follows:

- Iron and steel	1%
- Aluminum alloys	34%
- Other alloys	6%
- Chemicals (silicones, resins)	52%
- Semiconductors & solar cells	6%
- Others	1%

The end use in 1983 in Japan was as follows[3]:

Aluminum and non-ferrous alloys	-	64.5%
Chemicals (silicone resins, semiconductors etc)	-	29.0%
Iron and Steel alloys	-	1.5%
Refractories and other uses	-	5.0%

2.2 Market Overview

The 1985 shippable capacity and 1991 projected shippable capacity for the Western World silicon metal producers according to Elkem A/S: Presentation at INFACON '86 are as follows:

Table I - Plant Capacity

Country	Capacity 1985 (10^3t/yr)	Projected Capacity 1991 (10^3t/yr)
USA	153	168
Canada	25	25
Argentina	4	4
Brazil	39	130
France	70	80
W. Germany	12	12
Italy	24	29
Norway	125	140
Portugal	35	35
Spain	12	12
Sweden	22	22
Switzerland	10	10
Yugoslavia	40	40
South Africa	42	45
India	5	5
Australia	0	55
Total Western World	622	812

It is noteworthy that:

- Submerged arc furnaces are used at all production facilities.
- All plants in Japan have closed down now. Japan imports 70 - 80,000 t/yr.
- USSR produces about 70,000 t/yr of silicon.
- China produces about 33,000 t/yr.

- The only producer of silicon metal in Canada is SKW. Two 12 - 15,000 tonne furnaces operate at Becancour. A 7000-8000 t/yr plant operated by Elkem/Union Carbide at Beauharnois is closed now. Economy of scale is thought to be the reason for the closure. The current Canadian production is in the category of 96 - 99% and in 99 - 99.7% category. Approximately 12,000 tonnes are annually shipped to the U.S. and about 5000 tonnes to Japan.

The Western Worlds' present and projected Si-metal consumption in market segments 1985 - 1991 including annual growth rate (according to Elkem A/S: Presentation at INFACON '86, Rio de Janeiro, September 1986) are as follows:

Table II - Growth Rate in Si Consumption

End Use	Consumption 10^3 t/yr 1985	Projected 1991	% Growth/yr
Aluminum	310	330	1 - 2
Chemicals (Silicones, fillers semiconductors, solar cells)	160	230	6 - 7
Steel and Other	10	10	-
Total	480	570	3 - 3.5

New Si-metal plants announced or under construction in 1987 are:

- Pechiney/Pioneer Concrete - 13,000 tpy in Tasmania
- Icelandic Metals/RTZ - 32,000 tpy in Iceland

- Ispat Alloys in India - 2,750 tpy

- A number of announcements were made in Brazil.

Plant closings and output reductions were announced in France, Portugal, Norway and the Phillipines.

The primary market for silicon produced in British Columbia is expected to be Japan. Japan reduced its tariff on silicon imports in 1984. The Pacific Northwest region of North America is another market. The current U.S. Tariff (2 Dec. 1987) is as follows:
Schedule 632.42 Silicon metal <99.7 by weight 5.3% ad valorem
Schedule 632.43 Silicon metal >99.7 by weight 3.9% ad valorem.

2.3 Prices

The current price of silicon (Metals Week - March 4, 1988) is as follows.

0.35 Fe/0.07 Ca	-	68¢ (U.S.)/lb.
0.5 Fe/0.07 Ca	-	67.5¢ (U.S.)/lb.
1.0 Fe/0.07 Ca	-	67.0¢ (U.S.)/lb.

The price variation over the past two decades has been as shown in Figure 2. Japanese import prices have fluctuated between $1,000 U.S. to a high of $1,400 U.S. CIF per metric tonne between 1982 - 1986.

2.4 Projected Plant Size for B.C.

About 500 tonnes/yr of silicon is currently consumed in B.C. This amount is being supplied from outside the province.

It has been estimated[3] that 10,000 tonnes per year of silicon produced in B.C. could find a market as follows:

- 4,000 - 8,500 tonnes in Japan
- 500 - 4,000 tonnes in B.C.
- 1,000 - 2,000 tonnes in the U.S.A.

A production facility involving 20,000 tonnes/yr however, is economically more attractive than a 10,000 tonnes/yr plant. Market for this additional 10,000 tonnes/yr would be in the Pacific Rim, most likely in Japan.

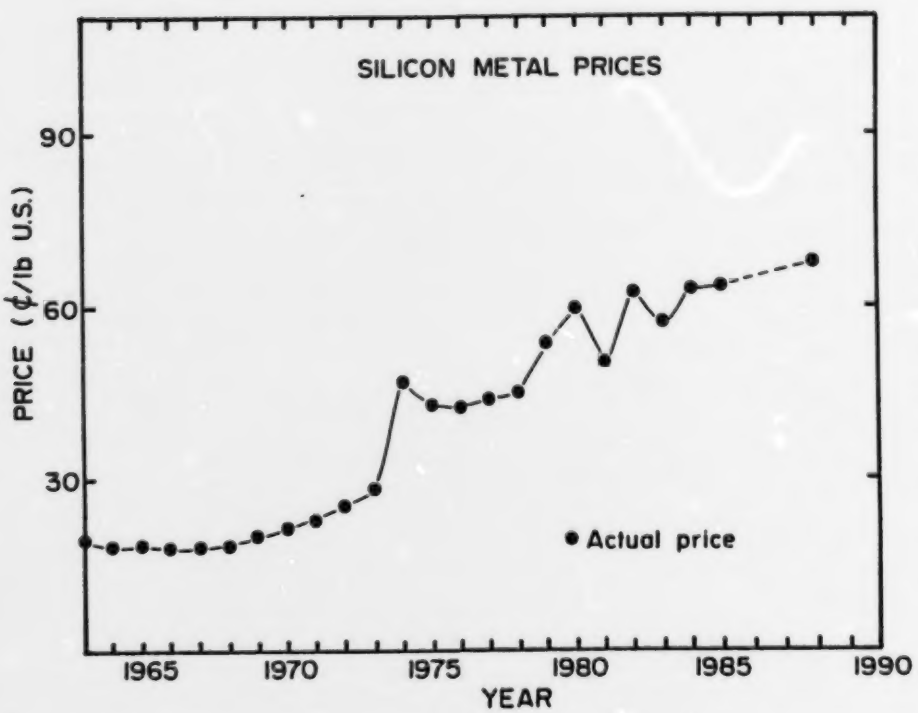

Figure 2: Price of silicon metal in the U.S. (¢)

3.0 CHOICE OF REACTOR CONFIGURATION

3.1 Thermodynamics and Process Kinetics

Carbon reduction of SiO_2 is the backbone of the current submerged arc technology. Depending on the temperature and other processing conditions a variety of reactions can occur. The basic thermodynamic data taken from "JANAF Thermodynamic Tables" have been subjected to computation analysis by Coldwell[9] to examine the relative ease of twelve reactions involving carbo-thermic reduction of silica. For ease of illustration only the following three most important reactions are considered here:

$$SiO_2 + 2C = Si + 2CO \quad (1)$$

$$SiO_2 + C = SiO + CO \quad (2)$$

$$Si + C = SiC \quad (3)$$

The free energy vs. temperature plot for those three reactions is shown in Figure 3. Bearing in mind that the more negative the free energy ΔF, the more favoured is the reaction (a positive value of ΔF means that the reaction will not occur), it is clear that silicon carbide formation will be favoured over silicon metal at temperatures below about 2000°K (1727°C).

Formation of silicon carbide becomes less favourable as the temperature increases. Above approximately 3200°K the reaction proceeds in the opposite direction i.e. silicon carbide starts breaking up into silicon and carbon. By contrast the reduction of silica (SiO_2) by carbon into silicon metal and silicon monoxide (SiO) becomes increasingly favourable as the temperature rises above approximately 2000°K. Below approximately 2000°K carbon reduction of SiO_2 into Si or SiO is thermodynamically not viable.

Formation of silicon carbide is well known to occur[10] in submerged arc furnaces. Accretions of SiC are found in cooler parts of the furnace when it is shut down and dug out. The reaction is favoured by an excess of carbon in the charge - what is commonly called an "over carbonized" or "overcoked" condition. The reason why silicon carbide is not found in the hotter parts of the furnace is probably because it reacts at high temperatures with silicon monoxide:

$$SiC + SiO \rightarrow 2\,Si + CO \qquad (4)$$

The silicon monoxide reaction (equation 2) is favoured by a deficiency of carbon and is the main cause of the loss of silicon during smelting in submerged electric arc furnaces. Silicon monoxide is a gas at reaction temperature and burns with a hot white flame producing clouds of fine white silica fume in open top furnaces. In a furnace operated with a cool top much of this is condensed on the carbon particles to be reduced to metal on their descent in the furnace.

3.2 The Proposed Transferred Arc Reactor

The reactor configuration proposed here is aimed at utilizing quartzite as the ore. Finely divided silica may well be treated more economically using other reactor configurations. It is to be noted that B.C. has numerous high quality quartzite deposits and virtually none of the high purity finely divided silica sand resources.

Reduction of silica with carbon involves the absorption of a considerable quantity of heat as well as attainment of a high temperature as discussed earlier. A high efficiency of the transferred arc (≅96%) makes it a logical candidate for carrying out silicon smelting. However, the well known transferred arc reactor configurations involving a vertically top mounted electrode are not considered suitable for this purpose. For example in the Plasmacan d-c transferred arc reactor[11] the cooler regions of the furnace will

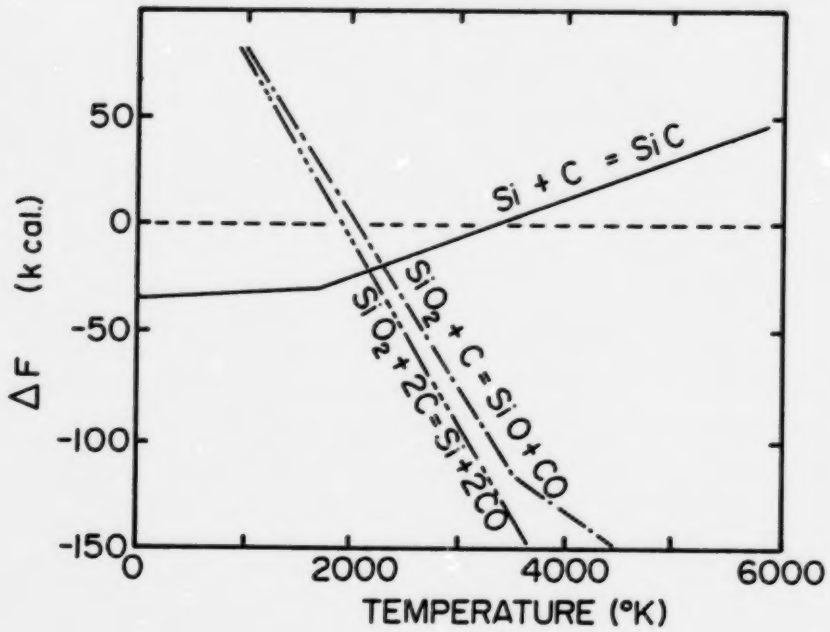

Figure 3: Free energies of three important reactions in the Si-O-C system (after Coldwell - Reference 9).

have silicon carbide accretion while the off gas outlets will be the areas where fumed silica deposits will build up quickly. Furthermore, the pneumatic feed system would likely necessitate not only crushing but grinding of the quartzite rock to 1-2 mm size. In addition to the cost of grinding, the transportation of the fines from the mine to the smelting site will have to be considered.

Our proposed configuration is shown schematically in Figure 4. The lining will be similar to that used in conventional submerged arc furnaces. The bottom of the furnace will be lined with carbon to contain the molten metal pool. A top mounted hopper will feed a mixture of crushed quartzite (6-16 mm size) and wood chips continuously or intermittently.

It would be logical to place a number of plasma generators arranged symmetrically about the furnace axis in a production plant. Uniformity of lining wear and continuity of operation, while one plasma generator is being replaced, could be achieved through such an arrangement. However, to keep the costs of the pilot study at a reasonable level, it is proposed to carry out the work with one generator only. This asymmetry of heating however, should not result in excessive wear of the lining material since much of the hot zone will be surrounded by the charge and the melt.

The plasma torch will create a cavity in the charge as milling progresses. When the cavity becomes large enough and the material below cannot support the weight of the charge column above, the charge will collapse. The arc length will be shortened momentarily (for tens of seconds) until the plasma column re-establishes the cavity. A viewing port will be provided to facilitate operation. The effect of charge collapse on the operation of the furance will be examined in the pilot study. The addition of wood chips should provide the channels needed for the gaseous reaction products to travel up along the column and escape near the top of the furnace. Pre-heating of the descending charge will be achieved thereby increasing thermal

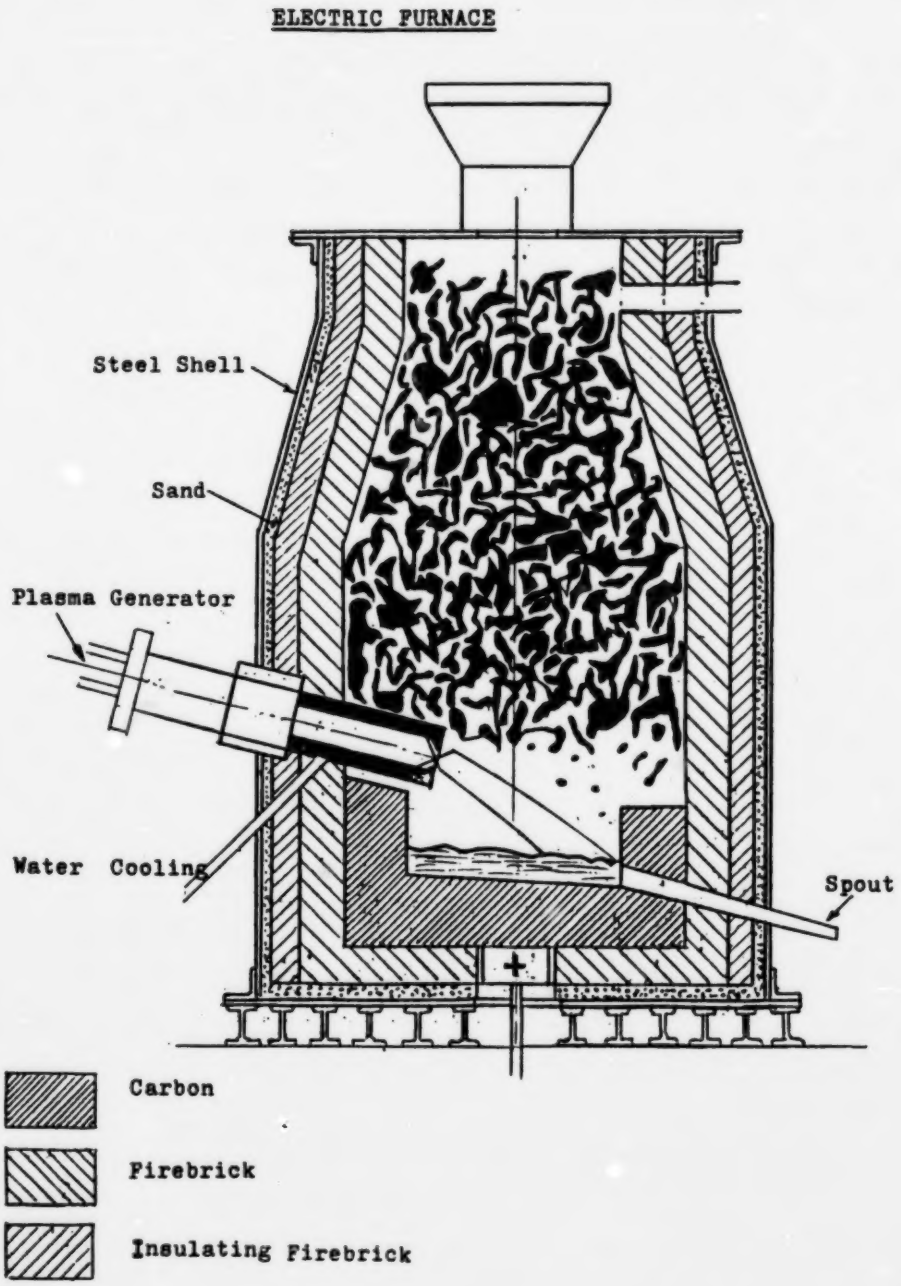

Figure 4: A schematic drawing of the proposed shaft furnace with a side mounted 1 MW transferred arc plasma generator for the pilot study. In the scaled up production plant possibly three plasma generators, located symmetrically around the circumference, will be appropriate.

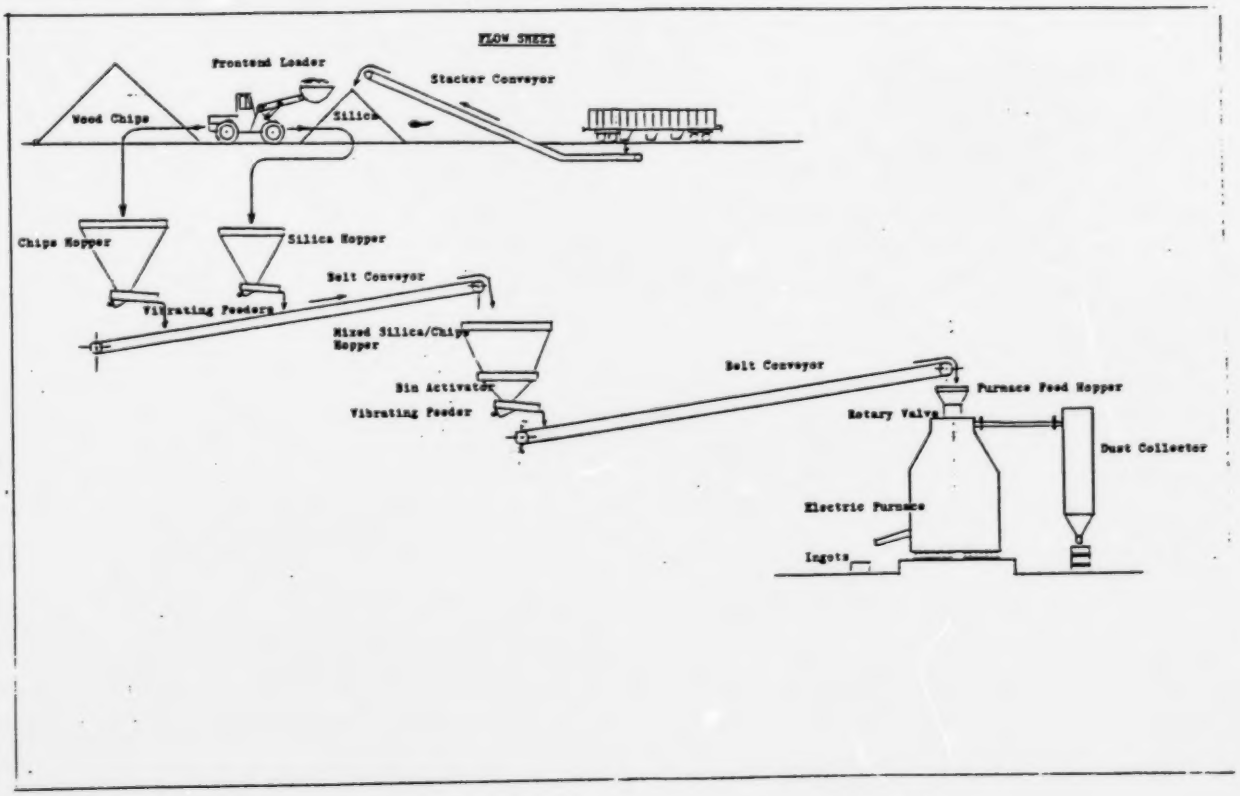

Figure 5: The flow sheet for the proposed pilot plant.

Site Plan

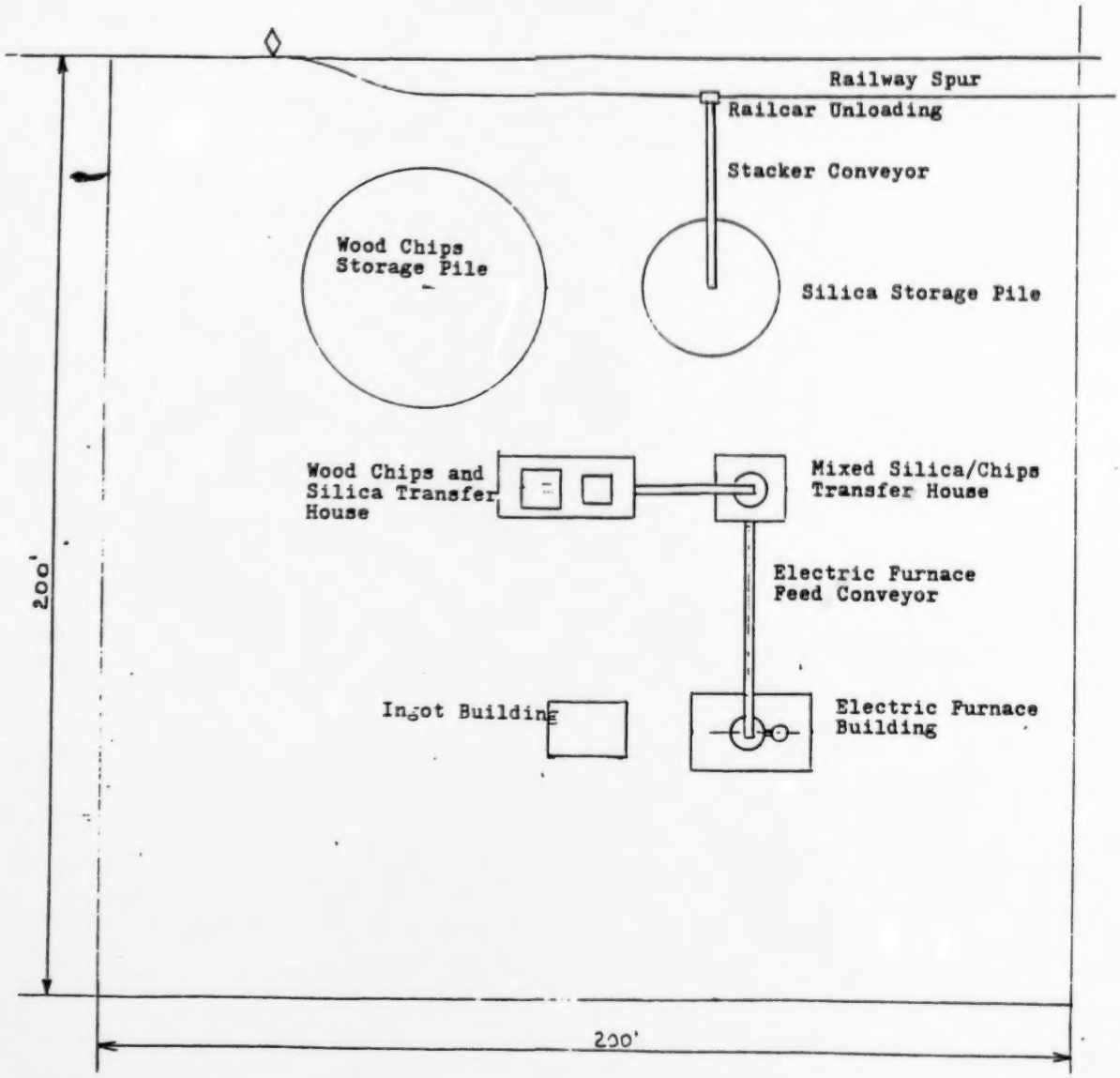

Figure 6: Site plan for the proposed pilot plant

efficiency. The need for cooling of the off gas will also be minimized. The descending charge will also serve a more important function i.e. the silicon carbide formed in the cooler parts of the charge and the SiO vapour condensed on the cooler charge will be continuously fed back into the reaction zone thereby making reaction 4 to occur in the high temperature smelting zone.

Since the plasma column will be surrounded with the charge, refractory losses are expected to be minimized. The melt may be tapped at intervals.

The wood chips will be carbonized during their descent and the resulting charcoal will act as a reductant. However, the volume of chips needed, if used alone for the optimum reduction process, may be too large. It is proposed to investigate natural gas (methane - CH_4) injection along with the plasmagen to aid the reduction process. Addition of other solid reductants may also be investigated in the pilot plant study.

4.0 PILOT PLANT LAYOUT

A pilot plant capable of producing 80 kg of 99-99.7% pure silicon/hr is proposed. Its flow sheet is shown in Figure 5. It is proposed that the front end loader will feed wood chips and crushed silica into two separate hoppers which in turn will feed through vibrating feeders on to a belt conveyor. That arrangement will permit a range of mixes to be investigated during the pilot study. The mixed feed will be transferred into another hopper and may be fed into the furnace feed hopper at a desired rate using another belt conveyor.

The site plan is shown in Figure 4. The pilot plant will be located adjacent to a rail line. Unloading will be done using a stacker conveyor,for stock piling of silica. Wood chips will be trucked in.

For the pilot plant a front end loader is considered adequate for materials handling from the storage piles to the transfer house.

The waste gas will be cleaned and released into the atmosphere. Casting moulds will be provided adjacent to the tapping spout of the furnace. Resin coated cast iron moulds are commonly used for that purpose.

5.0 COST ESTIMATE AND FINANCING OF THE PILOT PROJECT

5.1 Cost Estimate

The following cost estimate has been prepared, for budget purposes only, based on the best of the actual quotes received for various equipment. Judgement has been exercised regarding the type and quality of manpower needed to complete the pilot study. It is anticipated that the pilot study will provide results based on which commercial viability of production using plasma technology could be firmly established. It is estimated that the construction and commissioning of the pilot plant will take 6-9 months from the time the project is initiated and the equipment ordered. A further 2 years of actual operation of the pilot plant is anticipated for generating the necessary information. Table III below is a summary of the cost estimate.

5.2 Financing of the Pilot Plant

Preliminary discussions suggest that public, semi-public, and private sector capital may be available for the construction and operation of the pilot plant in the lower mainland area of British Columbia. The choice of the location is based on the availability of skilled scientific and engineering manpower, as well as land and water transportation facilities.

Table III - Cost Estimate for the Pilot Project

Item	Cost Can. $ in 1988
Capital Cost	
Electric furnace, refractories, materials handling, buildings and structures	
1 MW Plasma system (3 interchangeable torches) control panel, power supply, water cooling system, gas system, starter, cables and hoses	
Gas scrubbing, waste material disposal Gas, electricity and water connections Freight, federal taxes on plasma equipment, duty and contingencies Construction, supervision, co-ordination, office and travel expenses, commissioning	1,521,000
Operating Costs	
Utilities, raw materials	
Project engineer, scientist, 2 technicians, one labourer and one office staff	1,421,000
Total Project Cost	2,942,000

6.0 PRELIMINARY ANALYSIS OF COMMERCIAL PRODUCTION

6.1 Conventional Technology

Extensive operating experience with submerged arc furnaces world wide has generated a wealth of data on silicon production. The B.C. Ministry of Economic Development have made use of such figures[10] to carry out a conceptual site specific evaluation of silicon metal production in British Columbia[3]. Two sites were evaluated for that purpose, and two plant sizes, 10,000 tpy and 20,000 tpy were considered for modelling. Site specific details such as the cost of the raw materials, transportation cost, electrode, electric power cost, labour rate for each location and freight product delivered to the potential market as well as infra-structure costs were generated through in-house effort. Well established figures from the past plant operating experience elsewhere were used in that analysis. Examples of the latter per tonne of silicon produced are:

Quartz	-	2.7 t
Coal/coke	-	1.3 t
Wood chips	-	0.65 t
Electrodes	-	60 kg
Power	-	14,600 kWh
Labour	-	8.5 hrs/tonne

Rate of return, payback period etc were calculated for each site with variables such as power cost and silicon market price. That analysis led the B.C. Ministry of Economic Development to the conclusion that there exists an investment opportunity. A noteworthy finding of the said economic analysis has been the distribution of expenses, shown in Table IV below, for a 20,000 t/yr plant. Electrode paste was assumed as the electrode material for the purpose of modelling:

Table IV - Distribution Cost Expenses for Silicon Production in B.C. via Conventional Smelters

Capital	-	22%
Power	-	20%
Reductants	-	21%
coke/coal		
wood chips		
Electrode paste		
Ore (delivered)	-	7%
Freight (silicon)	-	7%
Operating	-	21%
Labour		
Maintenance		
Administration		
(etc.)		
Miscellaneous	-	2%

6.2 Plasma Technology

Based on the qualitative analysis to follow, it is anticipated that the production cost of silicon metal using plasma technology will be lower than that associated with the conventional submerged arc technology. The proposed pilot study is expected to verify that speculation.

6.2.1 Capital Cost

Due to its higher energy density, the plasma furnace will be compact hence less expensive. Cost savings may also be realized through elimination of the flicker control equipment. Voest Alpine[12] have operated a 45/60 tonnes D-C transferred arc furnace (5.8 m in diameter with 4 radial inclined torches, 6 MW each) for the production of low and high alloy steels. Their assessment is that the investment cost is slightly lower than for a comparable electric arc furnace. During a short continuous operation the costs achieved were similar to those of conventional electric furnaces. It was expected that in the long run the operating costs would be lower.

6.2.2 Electricity Considerations

In the context of silicon production it is not clear what advantage, if any, would be achieved through plasma technology compared to the conventional arc furnace production. Available information on ferro alloy production indicates that 20-30 percent lower operating costs are associated with plasma units[13]. The pilot plant would check this data for the case of silicon. This is important because silicon metal production is very energy intensive. It is to be noted that the submerged arc production figures have ranged from 12,500 - 14,600 kwh/tonnes of silicon under optimized operating conditions.

Canadian electricity prices are generally quite competitive with those of other silicon producing regions of the world as can be seen from Table V.

The electricity prices for industrial customers in the United States range from 3¢ U.S./kWh to 10¢ U.S./kWh for 93 percent of the U.S. electric utilities surveyed [Energy User News February 29, 1988, November 1987 data].

Canadian utilities electricity prices for large industrial customers range from 2.03¢/kWh (Trail, B.C.) to 4.75¢/kWh (Halifax, N.S.) for 50 MVA loads at 85 percent load factors. Hydro Quebec rates[14] for electric furnaces of the size required for a 20,000 t/yr silicon plant

Table V - Electricity Prices in the Silicon Producing Countries
Off-Shore 10 MW 80% Load Factor

(Electricity Council of London, U.K., October 1986 data converted to Canadian Currency)

Country	Cents/kW.h
France	6.55
Finland	4.81
Japan	11.5
Italy	5.77
Portugal	9.09
Spain	9.09
South Africa	3.50

was 2.6¢/kWh (85% load factor and 40 MW plant). Some provinces often offer various incentives to energy intensive industrial processes or plants, either in the form of electricity discounts or in terms of grants or loan guarantees, etc. B.C. electricity is available in the 2-3¢/kWh region which makes this province an extremely attractive area to produce siliton metal from the electricity price consideration as well.

6.2.3 Reductants and Plasmagen

Reductants constitute 21 percent of the projected cost of production of silicon in B.C. via submerged arc technology. It is anticipated that substantial savings could be realized if an optimum of woodchips to natural gas ratio could be established through the pilot plant work. Injection of methane with plasmagen or, if viable, methane plasma by itself may facilitate the following reaction:

$$2\ SiO_2 + CH_4 \rightarrow 2\ Si + CO_2 + 2\ H_2O \qquad (5)$$

Should that reaction 5 go to completion, the methane requirement would be 0.286 tonnes/tonne of silicon produced. The current price for that amount of methane (natural gas) in B.C. is $64. The price of wood

chips suitable for silicon metal production in B.C. ranges between $15-32/tonne. From the stand point of efficiency of utilization, anthracite or charcoal are better suited alternatives to the use of woodchips. There is however no existing charcoal making operation in British Columbia which could meet the needs of even the pilot study. Although coal is available in British Columbia, its ash content, (especially alumina and iron oxide) is too high to be suitable for use in silicon production. For example the ash content of Quinsam Coal (Vancouver Island) is 12.6 percent in the raw coal and drops down to 10.8 percent in the washed coal. The typical ash content is as follows:

Ash Analysis	Raw Coal	Washed Coal
SiO_2	37.4	35.0
Al_2O_3	20.1	25.3
Fe_2O_3	9.5	15.7
CaO	25.0	16.6
TiO_2	1.4	1.6
P_2O_5	0.7	0.6
SO_3	4.1	4.1
MgO, Na_2O, K_2O	0.6	0.9

It would be appropriate to investigate the percentage utilization of methane in the reduction process when CH_4 is used as a plasmagen. The viability of reaction 5 should be checked in a laboratory set-up as a precursor to the pilot study. Hydrogen, obtained through the decomposition of CH_4 at the high temperatures is likely to be a more effective reductant.

Stabilization of the plasma column may be achieved either through natural gas alone or by using a mixture of methane with nitrogen or argon. For the extreme case involving a nitrogen plasma (no methane) the plasma gas cost would be $56/tonne of silicon produced. Argon is approximately 5 times the cost of nitrogen ($280/tonne of silicon).

This added cost of plasmagen, (should it be other than natural gas), would most likely be offset by the savings in expensive reductants such as metallurgical coke ($175-200/tonne) needed for the submerged arc process. (To maintain electrical conductivity of the charge addition of coke is essential in the submerged arc process).

It is to be noted that the electrodes in the submerged arc process remain in contact with the charge, continuously or intermittently break as the smelting proceeds and the broken pieces act as the reductant along with coke and wood chips. By contrast the electrode in a transferred arc plasma generator comes in contact with the plasmagen only and not with the charge itself. The erosion process is slower. Typically a plasma d-c transferred arc electrode may require replacement every 200 hours of continuous operation. Of course the cost of the plasma generator itself will be an offsetting factor.

Projected electrode costs in the submerged arc production of silicon in B.C. are 6 percent if carbon paste is used, 14 percent if pre-baked electrodes are employed. Electrode cost will be substantially lower in the plasma process. This remains another important parameter to be ascertained through the proposed pilot study.

6.2.4 Operating Costs (labour, maintenance, administration, etc.)

Improved efficiency with plasma furnaces is expected since poking of the charge would be eliminated and the time for changing the electrode would be shorter.

In summary the pilot plant will establish critical information in the capital cost and in evaluating the reductant, plasmagen, electrode and other operating costs. A comprehensive business analysis would then be viable for the full production facility.

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